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IN FATIGUE TESTING OF COMPOSITES

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METHOD FOR MONITORING IN-PLANE SHEAR MODULUS IN FATIGUE TESTING OF COMPOSITES

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ABSTRACT

A method was developed for nondestructive intermittent monitoring of in-plane shear modulus of composite specimens undergoing fatigue loading. A modified three-rail shear fixture was designed for easy mounting and disassembly. The shear strain is measured with an extensometer attached to the rails of the fixture. Modulus results were in excellent agreement with independently measured values. The method is ideal for studying damage development, since the in-plane shear modulus is sensitive not only to transverse matrix cracking but also to longitudinal cracking and delamination.

KEYWORDS: Test methods, shear testing, rail-shear technique, damage development, fatique testing, stiffness degradation

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INTRODUCTION

Damage in composite laminates consists of the development and accumulation of numerous defects. The basic failure mechanisms, i.e., intralaminar and interlaminar matrix failures, have been observed and identified [1-3]. They can be studied and characterized by means of a variety of nondestructive methods, such as X-radiography, ultrasonics, acoustic emission, and edge replication.

Under fatigue conditions, damage in crossply laminates consists of transverse matrix cracking, longitudinal matrix cracking, delaminations at the intersection of matrix cracks, and fiber fractures [4]. Damage development depends on the applied cyclic stress level and consists of three stages: (1) damage occuring during the first fatigue cycle consisting of transverse matrix cracking, (2) damage developing during the first 80% of the logarithmic lifetime of the material and consisting of transverse matrix cracks up to a saturation density (Characteristic Damage State), and (3) damage occuring in the last 20% of the logarithmic lifetime and consisting of longitudinal matrix cracking, local delaminations and fiber fractures [5].

The state of damage is intimately related to the three most important properties of the material, stiffness, strength and life. Of these three properties, stiffness is related to damage in a more deterministic way. Furthermore, stiffness can be measured frequently during damage development in a nondestructive manner. Thus, stiffness is an important measure of damage [6]. Some analytical procedures have been developed for relating stiffness reduction to damage state for some forms of damage, such as matrix cracking and delaminations [7-10].

The most commonly monitored stiffness component is the axial modulus which is dominated by the 0-deg plies. Therefore, this modulus is only mildly

sensitive to transverse matrix cracking and insensitive to longitudinal matrix cracking and delamination. The axial modulus decreases with transverse crack density up to the limiting value (CDS level). Thereafter, it remains nearly constant over a long portion of the fatigue life, up to the point where excessive fiber breakage occurs just prior to failure. Since longitudinal cracking is a critical failure mechanism and a precursor to final failure, it is important to monitor it nondestructively by either transverse tensile or in-plane shear testing. Of these two types of tests, the former is impractical in view of the coupon configuration. The most feasible approach is the in-plane shear test.

The importance of measuring several stiffness parameters has been recognized by other investigators and techniques have been used for measuring, in addition to axial Young's modulus, Poisson's ratio, in-plane shear modulus and transverse flexural modulus [11,12]. However, only qualitative trend information was obtained for the last two properties.

This paper describes a method employing a modified three-rail shear fixture for the nondestructive monitoring of in-plane shear modulus during fatigue testing.

DESCRIPTION OF FIXTURE

The fatigue coupons tested were standard straight-edge coupons, 2.54 cm (1 in.) wide and 23 cm (9 in.) long with 3.81 cm (1.5 in.) glass/epoxy tabs. A balanced three-rail shear fixture was designed to fit over the fatigue coupon for determination of the shear modulus (Fig.1). It consists of two pairs of 2.54 cm (1 in.) wide outer rails and a pair of 5.08 cm (2 in.) wide center rails. The rails, having one face roughened for better gripping, are clamped over the coupon exposing two 1.27 cm (0.5 in.) wide strips as the test

section. Thus, a total of 2.54 cm (1 in.) length of the specimen, representing approximately 17% of the entire gage length of the coupon is tested for shear modulus.

The rails of each pair are of unequal length. One rail from each pair of outer rails is extended into a clevis. These two long rails are connected by a pin to keep them parallel. The load is transmitted through the central hole of a triangular plate and then through the outer two holes with pins to the clevises of the outer rails. The central rails are also of unequal length. The longer rail has an extension at the bottom of the fixture with an elongated central hole. This extension fits into the clevis attached to the piston of the electrohydraulic testing machine. The rails with their extensions are designed so that the loading axis passes through the midplane of the coupon. The rails are clamped against the coupon by means of bolts as shown in Fig.1.

A shallow rectangular groove is machined on the outer face of the short central rail and one of the outer rails. The two small screws shown in the figure in those grooves are used to hold two bars for attachment to the arms of the extensometer for measurement of the shear deformation. The shear strain is obtained from the relative displacement of the center rails and the outer rails. This is measured by means of a 1.27 (0.5 in.) extensometer mounted on two bars attached to one center rail and one outer rail, as shown in Fig.2.

The fixture can be mounted quickly after removing the specimen from the fatigue machine. During assembly and disassembly the fixture with the specimen rests on a jig designed to prevent lateral movement during tightening or loosening of the bolts (Fig.3). Before clamping the rails onto the specimen, strips of masking tape are applied on both sides of the specimen. This helps to increase the gripping action of the rails and protects the specimen surface

from damage due to the clamping pressure. The latter becomes more important when using this shear test as a measure of damage development during fatigue.

TEST PROCEDURE

After assembly and mounting, the long center rail is attached through a clevis to the base of the testing machine, in this case to the movable piston of the electrohydraulic machine (Fig.2). The extened outer rails are connected to a crossbar which is connected to the crosshead of the loading frame by means of a clevis link. The assembled fixture with the specimen is then cycled in the testing machine for approximately 10 cycles to a load of approximately 10% of the maximum load to be applied during the test. This procedure relieves all slack in the specimen and fixture.

During the test, continous records of the load from the testing machine load cell and strain from the extensometer were obtained. The signals were amplified and recorded by a digital oscilloscope (Norland 3001). The data was then transferred to a microcomputer for processing and plotted on an X-Y plotter (HP 7470A).

The in-plane shear stress was computed as follows:

$$\tau_{xy} = \frac{P}{2bh}$$

where P = applied load

b = coupon width

h = coupon thickness

The in-plane shear strain was obtained as follows:

$$\gamma_{xy} = \frac{\delta}{w}$$

where δ = relative displacement of center and outer rails

w = width of exposed test section (1.27 cm, 0.5 in.)

The value of the in-plane shear modulus was determined as the initial slope of the shear stress versus shear strain curve:

$$G_{xy} = \frac{\tau_{xy}}{\gamma_{xy}}$$

EVALUATION OF THE METHOD

The reliability of the fixture was evaluated by testing undamaged specimens using both the extensometer described before and strain gages. The latter were applied on the exposed test sections of the coupon at 45-deg. to the loading direction. Figure 4 shows shear stress versus shear strain curves for a $[0/90_2]_s$ crossply graphite/epoxy laminate obtained by using the extensometer and strain gages. The agreement between the two curves is very satisfactory.

The value of the in-plane shear modulus for the crossply coupon tested must be equal to the in-plane shear modulus G_{12} of the unidirectional material. The latter was measured by conducting a uniaxial tensile test on a 10-deg off-axis unidirectional coupon. This coupon was instrumented with a two-gage rosette with the gage elements oriented at +45 and -45-deg with the fiber direction. In this case, the in-plane shear strain referred to the fiber direction is equal to the algebraic difference of the two strains measured.

Shear stress versus shear strain curves obtained for the crossply coupon with the fixture described and the off-axis tensile coupon are shown in Fig.5. The agreement is very satisfactory, despite the fact that the aspect ratio of the test section in the rail shear fixture is not as high as recommened by ASTM.

The shear fixture was then applied to the measurement of shear modulus degradation during cyclic loading of $[0/90_2]_s$ graphite/epoxy (AS4/3501-6). Typical shear stress versus shear strain curves are shown in Figs.6 and 7. The solid curves represent the behavior of the undamaged specimen, whereas the dashed curves correspond to the damaged specimen after 1,000 and 4,000 cycles under tension-tension (R=0.1) fatigue loading at a maximum cyclic stress of 85% of the static ultimate. The reduction in shear modulus at 1,000 cycles is due entirely to the transverse matrix cracking, which in this case reaches its limiting density (CDS level) after the first cycle. The additional reduction measured at 4,000 cycles is due only to the longitudinal matrix cracks developing at that point. Radiographs illustrating the damage after 1,000 and 4,000 cycles are shown in Fig.8.

Although the initial in-plane shear modulus appears to correlate well with longitudinal cracking, the shear strain energy loss (the shaded area in Fig. 6 and 7) could be used as an additional measure of damage.

It should be noted that longitudinal matrix cracking is usually accompanied by delamination at the intersections of the transverse and longitudinal cracks. This delamination also has an influence on shear modulus reduction.

SUMMARY AND CONCLUSION

A method was developed for nondestructive intermittent monitoring of inplane shear modulus of specimens undergoing fatigue loading. The method employs a modified three-rail shear fixture designed for easy mounting and disassembly and an extensometer. This obviates the need for strain gages

which are costly and do not stand well under fatigue loading. Modulus results were in perfect agreement with independently measured values. The method is ideal for studying damage development, since the in-plane shear modulus is sensitive not only to transverse matrix cracking but also to longitudinal cracking and delamination.

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FIGURE CAPTIONS

Fig. 1. Fixture for Measuring In-Plane Shear Modulus of Composite Fatigue Test Specimens

Fig. 2. Rail Shear Fixture Mounted in Testing Machine

Fig. 3. Jig and Assembly of Fixture in Jig

Fig. 4. Shear Stress vs. Shear Strain Curves for AS4/3501-6 Graphite/Epoxy $[0/90_2]_s$ Laminate Obtained with an Extensometer and with Strain Gages on Rail Shear Specimen

Fig. 5. Shear Stress vs. Shear Strain Curves Obtained with the Rail Shear Fixture and Extensometer and from a 10-deg Off-Axis Specimen with Strain Gages

Fig. 6. Shear Stress vs. Shear Strain Curves of $[0/90_2]_s$ AS4/3501-6 Graphite/Epoxy Laminate Before and After Cyclic Loading

Fig. 7. Shear Stres vs. Shear Strain Curves of $[0/90_2]_s$ AS4/3501-6 Graphite/Epoxy Laminate Before and After Cyclic Loading

Fig. 8. X-Radiographs of $[0/90_2]_s$ Graphite/Epoxy Specimen under Fatigue Loading at $R = 0.1$ and $\sigma_{max} = 0.85\ F_{xT}$

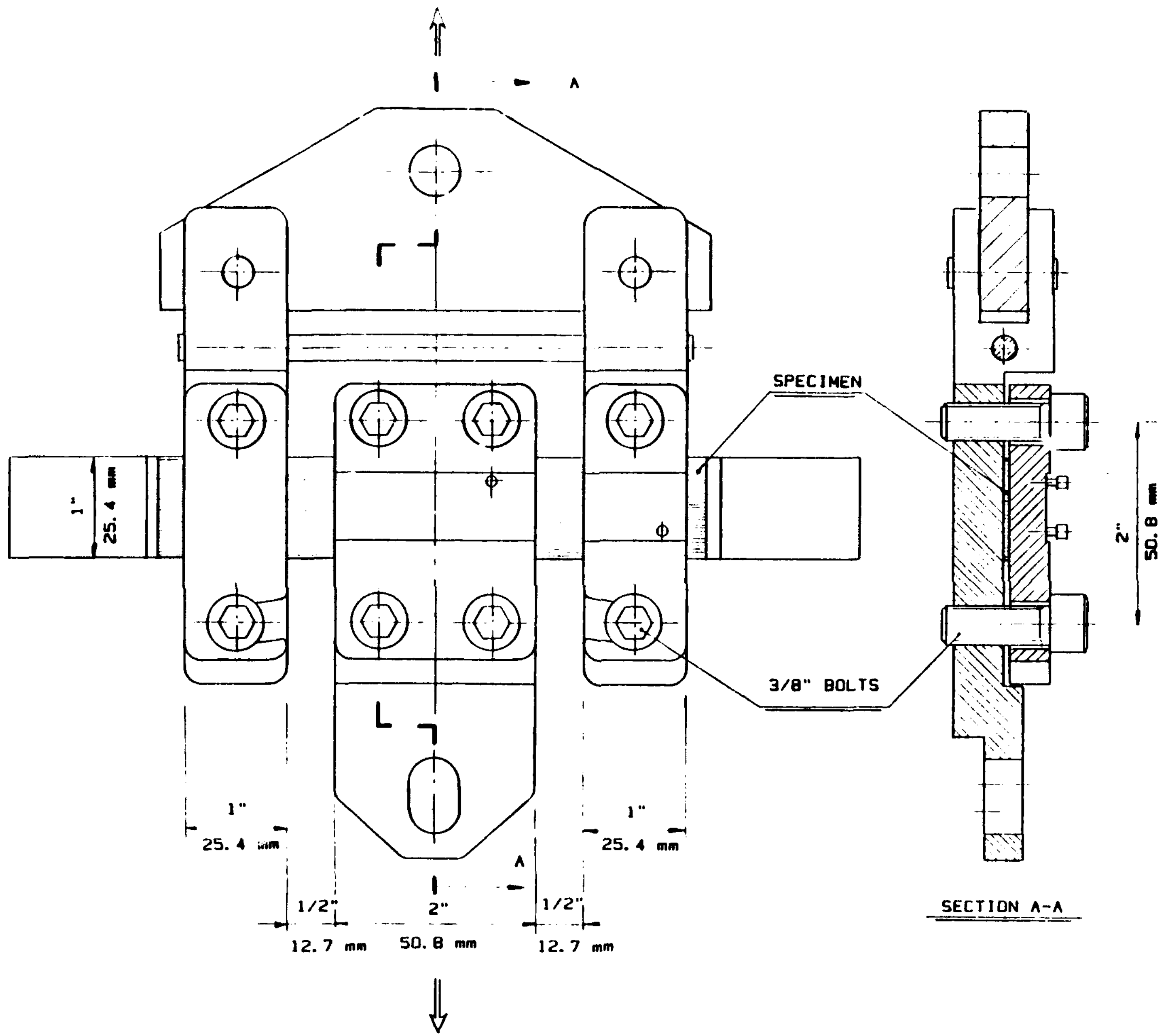


Fig. 1. Fixture for Measuring In-Plane Shear Modulus of Composite Fatigue Test Specimens

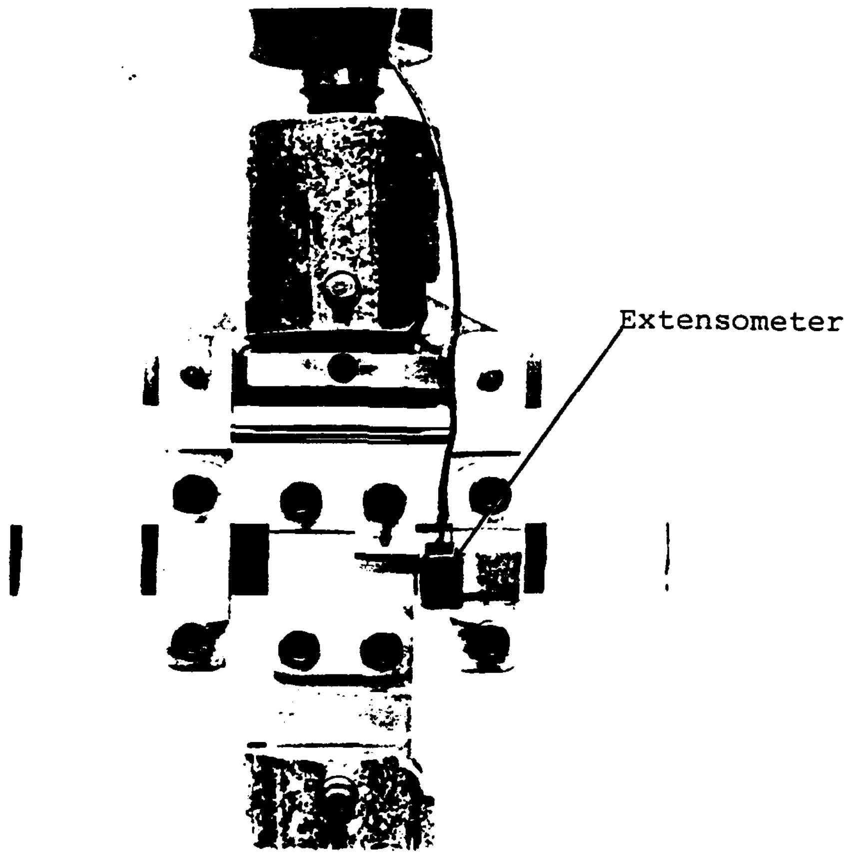
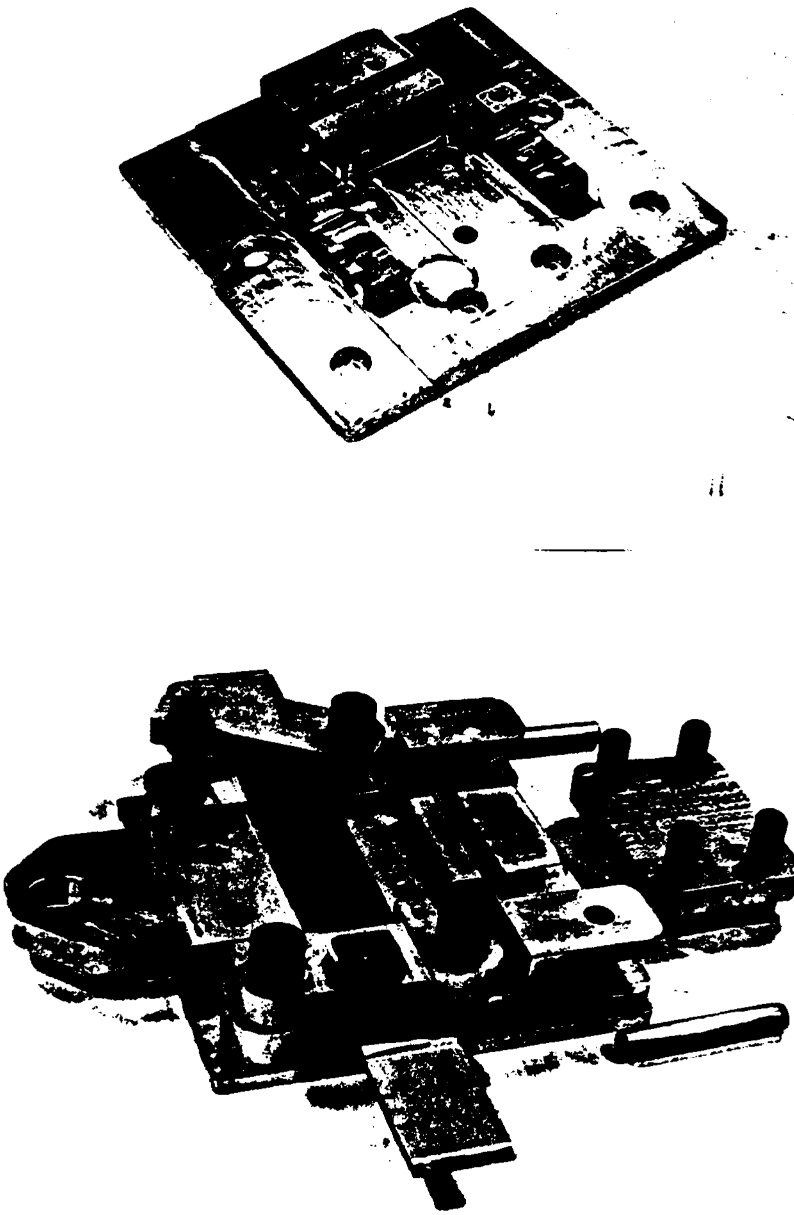


Fig. 2. Rail Shear Fixture Mounted in Testing Machine



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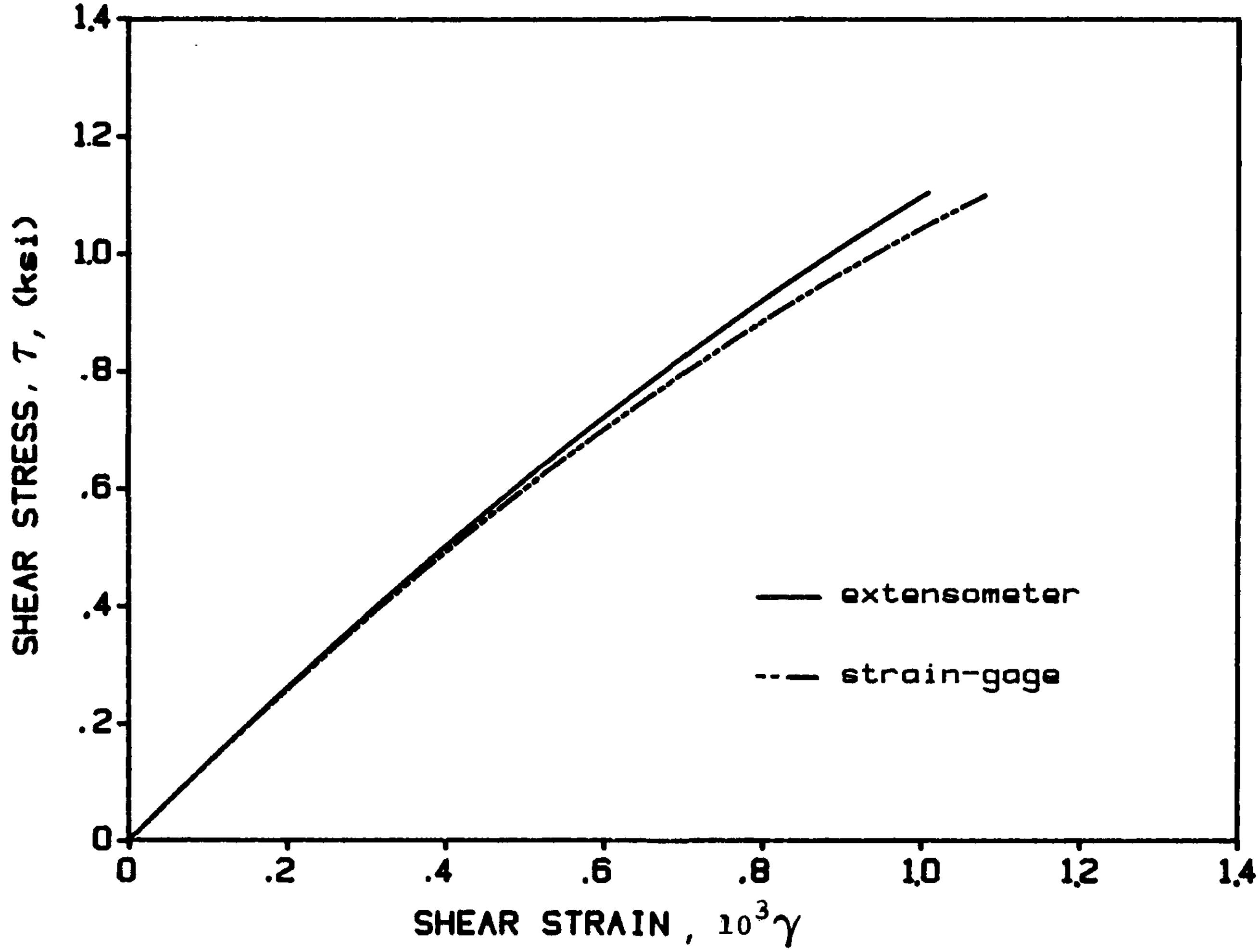


Fig. 4. Shear Stress vs. Shear Strain Curves for AS4/3501-6 Graphite/Epoxy $[0/90_2]_s$ Laminate Obtained with an Extensometer and with Strain Gages

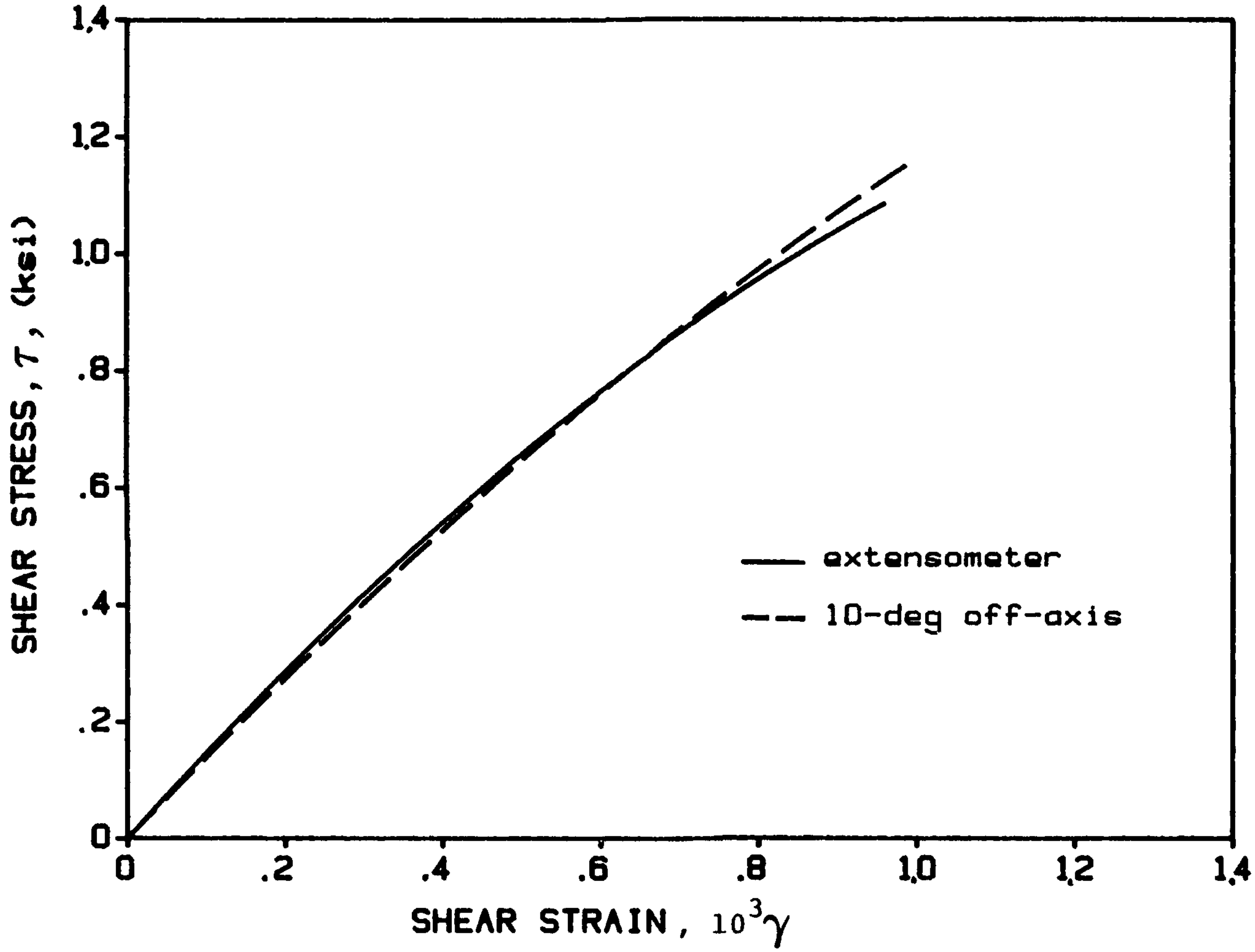


Fig. 5. Shear Stress vs. Shear Strain Curves Obtained with the Rail Fixture and Extensometer and from a 10-deg Off-Axis Specimen with Strain Gages.

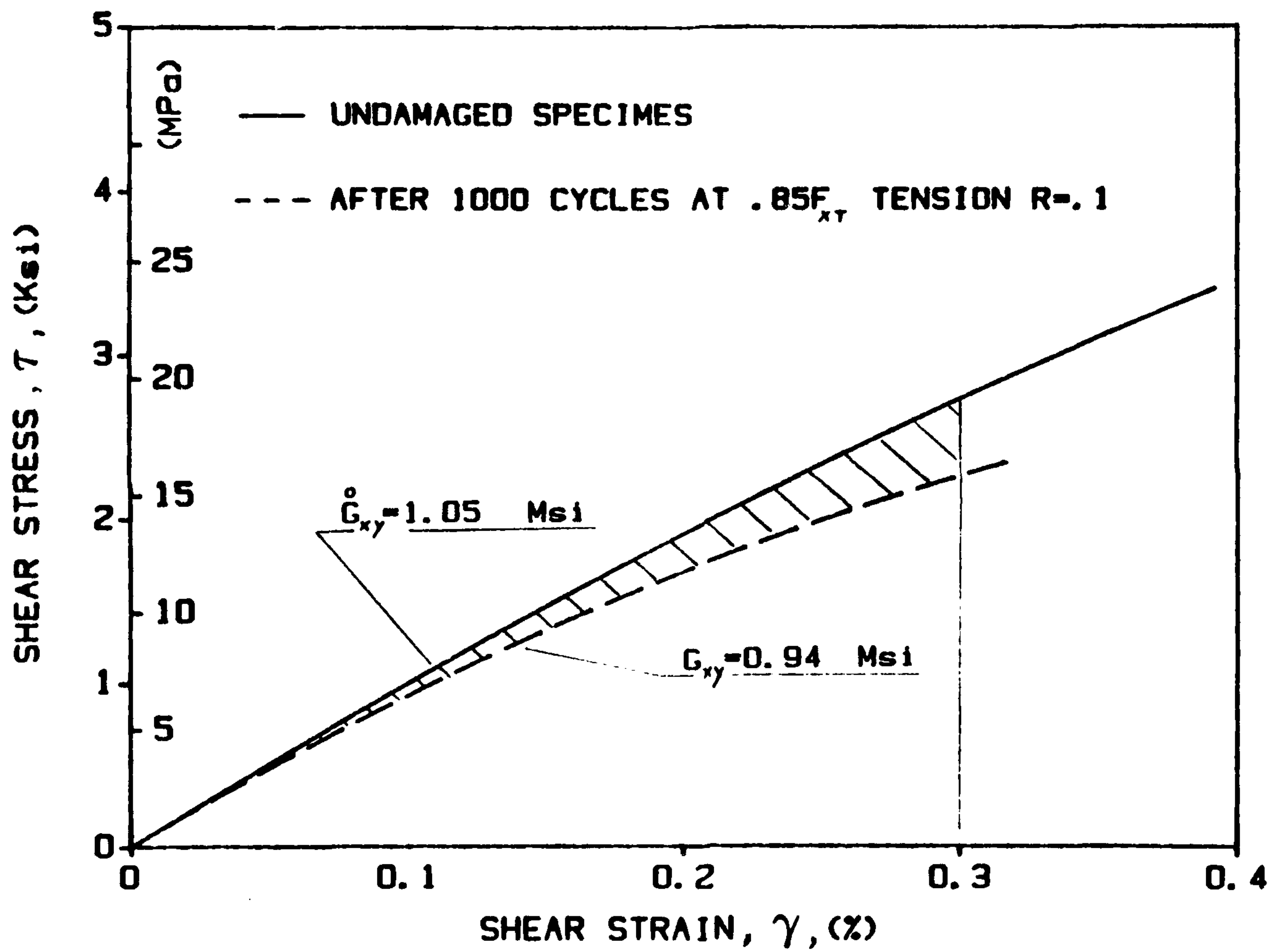


Fig. 6. Shear Stress vs. Shear Strain Curves of $[0/90_2]_s$ AS4/3501-6 Graphite/Epoxy Laminate Before and After Cyclic Loading

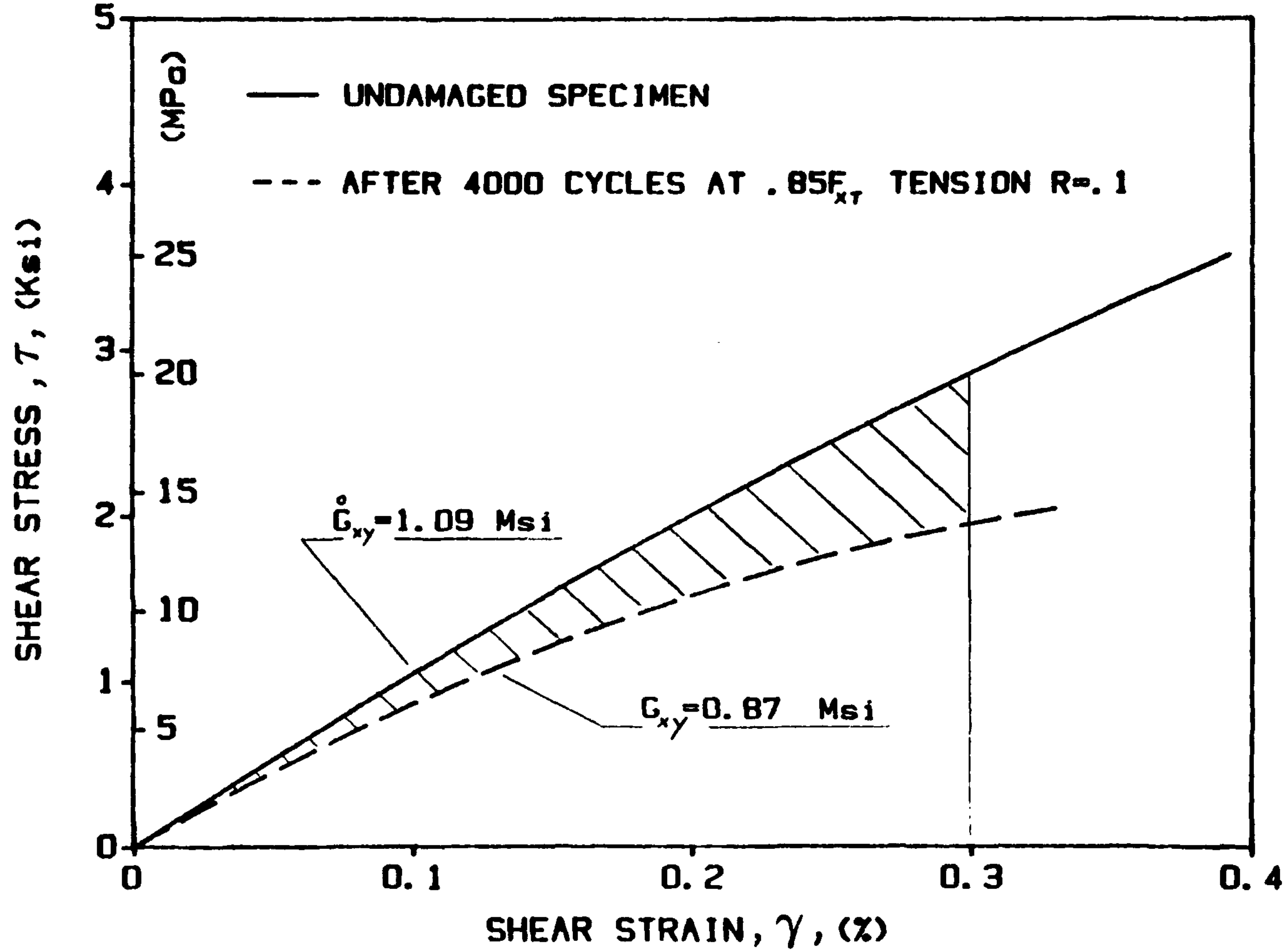
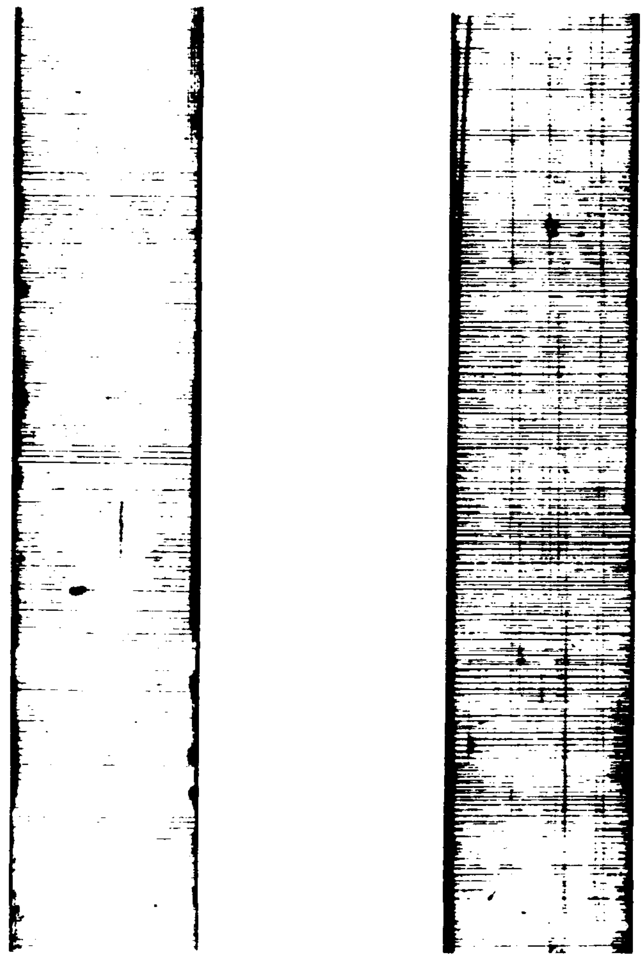


Fig. 7. Shear Stress vs. Shear Strain Curves of $[0/90_2]_s$ AS4/3501-6 Graphite/Epoxy Laminate Before and After Cyclic Loading



N = 1000 N = 4000

Fig. 8. X-Radiographs of $[0/90_2]_s$ Graphite/Epoxy Specimen under Fatigue Loading with $R = 0.1$ and $\sigma_{max} = 0.85F_{xT}$

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